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MAGIC discovery of the distant quasar 4C +21.35 in VHE gamma rays

J. Becerra-González*, A. Stamerra, K. Saito, T. Terzic, D. Mazin, E. Prandini, J. Sitarek, L. Maraschi, F. Tavecchio, A. Treves on behalf of the MAGIC Collaboration
Instituto de Astrofísica de Canarias, C/ Vía Láctea s/n,
38205 San Cristobal de la Laguna, Tenerife (Spain)
E-mail: `jbecerra@iac.es`

The MAGIC telescopes discovered Very High Energy (VHE, E>100 GeV) γ-ray emission coming from the distant Flat Spectrum Radio Quasar (FSRQ) 4C +21.35 (PKS 1222+21, z=0.432) [1, 2]. It is the second most distant VHE gamma-ray source, with well measured redshift, detected until now. The observation was performed on 2010 June 17 (MJD 55364.9) using the two 17 m diameter imaging Cherenkov telescopes on La Palma (Canary Islands, Spain). The MAGIC detection coincides with high energy MeV/GeV γ-ray activity measured by the Large Area Telescope (LAT) on board the *Fermi* satellite. The averaged integral flux above 100 GeV measured by MAGIC is $(4.6 \pm 0.5) \times 10^{-10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (~ 1 Crab Nebula flux). The MAGIC measured spectrum can be well described by a simple power law from 70 GeV to at least 400 GeV. The combined VHE and MeV/GeV spectrum corrected for the absorption by the extragalactic background light is consistent with a simple power law from 3 GeV up to 400 GeV, suggesting that the emission is coming from the same single component in the jet. The absence of a spectral cutoff indicates that the γ-ray emission region is outside of the Broad Line Region. We also detected fast variability in VHE γ-rays with a flux doubling time of $8.6^{+1.1}_{-0.9}$ minutes. This fast variability together with the spectral signatures are very challenging for the present jet emission models of FSRQs.

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1. Introduction

Blazars are active galactic nuclei hosting powerful relativistic jets pointing toward the observer. They are characterized by strong non-thermal emission extending across the entire electromagnetic spectrum, from radio up to γ-rays. Flat Spectrum Radio Quasars (FSRQs) are a subgroup of blazars which present broad emission lines often accompanied by a Òbig blue bump" in the optical-UV region, associated with the thermal emission from the accretion disk. Only ~ 40 AGNs have been detected in Very High Energy (VHE) γ-rays, out of which only two of them have been classified as FSRQ. The detection of the FSRQ 4C +21.35 (PKS 1222+21, $z = 0.432$,[5]) by MAGIC makes it the second most distant object with known redshift (after 3C 279, the most distant VHE source detected until now, z=0.536 [3, 4]) ever detected at VHE[1].

In this proceeding, we will present the MAGIC discovery of this source which was detected during a γ-rays flare announced by the *Fermi*/LAT collaboration and its physics implications.

2. MAGIC discovery

4C +21.35 was observed by MAGIC on June 17 (MJD 55364) for 30 minutes as part of a Target of Opportunity program triggered by an increased flux in the *Fermi* energy band [7]. During this detection by MAGIC the source was close to the brightest flare ever observed by the *Fermi* Large Area Telescope (LAT) [8].

MAGIC consists of two 17 m diameter Imaging Atmospheric Cherenkov Telescopes (IACT). The data were taken at zenith angles between 26° and 35°. Stereoscopic events, triggered by both telescopes, were analyzed in the MARS analysis framework [10]. Details on the analysis can be found in [11] whereas the performance of the MAGIC telescopes stereo system will be discussed in detail in a forthcoming paper [9]. The signal evaluation was performed using the θ^2 distribution (squared angular distance between the true and reconstructed source position), see the Figure 1. We got an excess of 190 γ-like events (6 γ/min.) above a background of 86 events, which corresponds to a statistical significance of 10.2 σ using eq. 17 in [12]. The energy threshold of this analysis is ≈ 70 GeV.

3. Very High Energy Spectrum

The energy spectrum measured by MAGIC extends from 70 GeV to 400 GeV (Figure 2) and it is well-described by a simple power law of the form:

$$\frac{dN}{dE} = N_{200} \left(\frac{E}{200\,\mathrm{GeV}} \right)^{-\Gamma} \tag{3.1}$$

with a photon index $\Gamma = 3.75 \pm 0.27_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}}$ and a normalization constant at 200 GeV of $N_{200} = (7.8 \pm 1.2_{\mathrm{stat}} \pm 3.5_{\mathrm{syst}}) \times 10^{-10}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$, yielding an integral flux $(4.6 \pm 0.5) \times 10^{-10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (≈ 1 Crab Nebula flux) at E$>$ 100 GeV. For energies higher than 400 GeV no significant excess was found but two upper limits corresponding to 95% confidence level (C.L.) have

[1]The redshift measurement ($z = 0.444$) of the VHE BL Lac 3C 66A has large uncertainties [6].

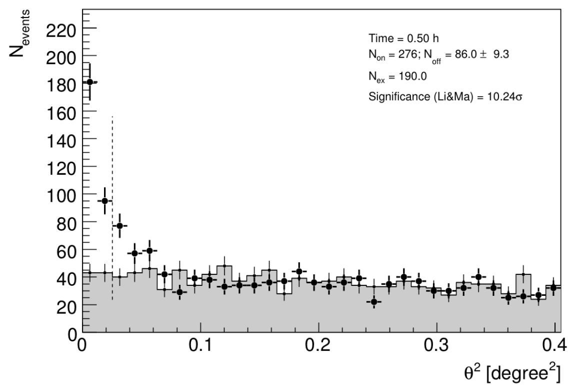

Figure 1: Distribution of the squared angular distance (θ^2) for events in the direction of 4C +21.35 (black points) and normalized off-source events (grey histogram). The signal is extracted in the θ^2-region denoted by the vertical dashed line.

been derived. The method used for the spectral reconstruction is the so-called "Tikhonov" unfolding algorithm [17], which takes into account the finite energy resolution of the instrument and the biases in the energy reconstruction. The systematic uncertainty of the analysis (studied by using different cuts and different unfolding algorithms) is shown by the grey area.

The deabsorbed spectrum is shown by the blue squares in Fig. 2, where the EBL model of [13] has been used. It is well fitted by a power law with an intrinsic photon index of $\Gamma_{\rm intr} = 2.72 \pm 0.34$ between 70 GeV and 400 GeV. Uncertainties caused by the differences between the EBL models are represented in Fig. 2 by the blue-striped area. The corresponding spread is smaller than the systematic uncertainties of the MAGIC data analysis.

Using the χ^2 difference method we studied the possibility of a cut-off in the energy spectrum. We tried to fit the spectrum by a broken power law with different photon indexes and values for the cut-off. We concluded from this study that with the available statistics, at the 95% C.L. we cannot exclude the presence of a cut-off above 130 GeV for a photon index 2.4 (the lowest possible value compatible with fit uncertainties and with the *Fermi*/LAT data) or above 180 GeV for a photon index 2.7.

4. Spectral Energy Distribution

The high-energy Spectral Energy Distribution (SED) is shown in Figure 3 where the MeV/GeV energy range spectrum from *Fermi*/LAT and the GeV/TeV spectrum measured by MAGIC are combined. The source showed a significant flare in the *Fermi* band lasting $\sim$3 days, with a peak flux on 2010 June 18 (MJD 55365) [8]. During the 1/2 hr MAGIC observation there is a gap in the LAT exposure, so we analyzed the closest data available, a period of 2.5 hr (MJD 55364.867 to 55364.973) centered around the MAGIC observation. Given the short observation time (chosen in order to be as much contemporaneous as possible with the MAGIC data) there is no detection above 2 GeV in the *Fermi*/LAT data, but an upper limit at the 95% C.L. in the energy range $2-6.3$ GeV

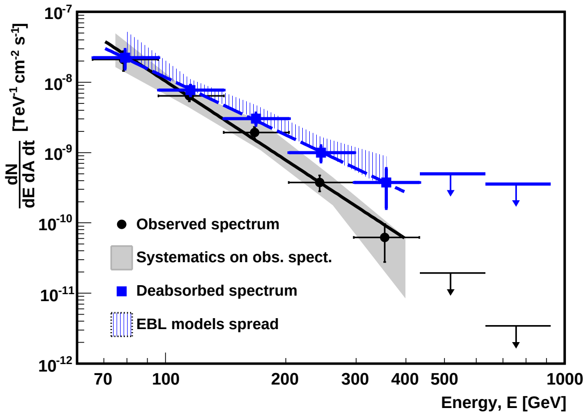

Figure 2: Differential energy spectrum of 4C +21.35 as measured by MAGIC on 2010 June 17. Differential fluxes are shown as black points, upper limits (95% C.L.) as black arrows. The black line is the best fit to a power law. The grey shaded area represents the systematic uncertainties of the analysis. The absorption corrected spectrum and upper limits using the EBL model of [13] are shown by the blue squares and arrows; the dashed blue line is the best fit power law. The blue-striped area illustrates the uncertainties due to differences in the EBL models of [14, 15, 16] and [3].

has been calculated together with the spectral points up to 2 GeV and combined with the MAGIC data in the SED shown in Fig. 3.

If we extrapolate the intrinsic MAGIC spectrum to lower energies we can see that there is a potentially smooth connection between the *Fermi*/LAT and MAGIC extrapolated data and the photon index steepens from 1.9 in the *Fermi*/LAT range to 2.7 in the MAGIC range. These results agree with the analysis of larger temporal intervals during this flare and during the whole active period, in which the source spectrum is well described by a broken power law with an energy break between 1 and 3 GeV [8]. Furthermore it is found that the high energy tail ($E > 2$ GeV) of the *Fermi*/LAT spectrum of 4C +21.35 extends up to 50 GeV, with a photon index in the range 2.4-2.8.

5. Source Variability

Thanks to the strength of the signal even if the observation time is as short as 30 minutes, a variability study is possible. In Fig. 4 the light curve binned in 6 minutes long intervals is shown. It reveals a flux variation within the 30 minutes of observation time. The hypothesis of a constant flux is rejected ($\chi^2/NDF = 28.3/4$) with high confidence (probability $< 1.1 \times 10^{-5}$). The flux of the background events surviving the γ/hadron selection cuts is compatible with being constant and hence we can exclude a variation of the instrument performance during the observation.

To quantify the variability time scale we performed an exponential fit (solid black line in Fig. 4). A linear fit is also acceptable but does not allow us to define a time scale unambiguously. For the exponential fit the doubling time of the flare is estimated as $8.6^{+1.1}_{-0.9}$ minutes. The derived timescale corresponds to the fastest time variation ever observed in an FSRQ in the VHE range and in any other energy range [18], and is amongst the shortest measured from any TeV emitting source [19, 23].

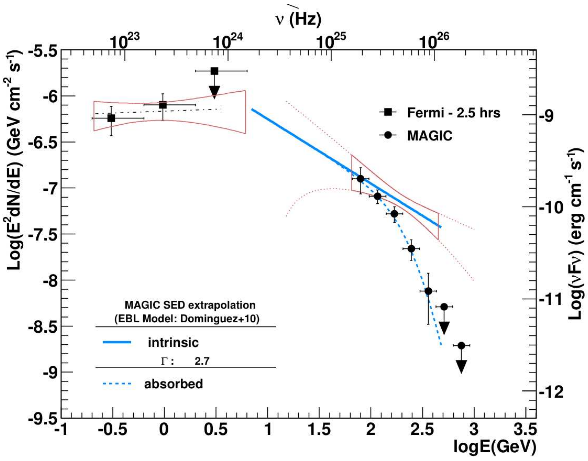

Figure 3: High energy SED of 4C +21.35 during the flare of 2010 June 17 (MJD 55364.9), showing *Fermi*/LAT (squares) and MAGIC (circles) differential fluxes. A red bow tie in the MeV/GeV range represents the uncertainty of the likelihood fit to the *Fermi*/LAT data. The unfolded and deabsorbed spectral fit of the MAGIC data is also shown as a red bow tie, extrapolated to lower and higher energies (dotted lines). A thick solid line (photon index $\Gamma = 2.7$) indicates a possible extrapolation of the MAGIC deabsorbed data to lower energies. The thick dashed line represents the EBL absorbed spectrum obtained from the extrapolated intrinsic spectrum using the model of [13].

6. Conclusions

As we have discussed, the almost simultaneous VHE and GeV spectra are consistent with a single power law with index $\sim 2.7 \pm 0.3$ between 3 GeV to 400 GeV, without a strong intrinsic cut-off. This evidence suggests that the 100 MeV - 400 GeV emission belongs to a unique component, peaking at $\approx 2-3$GeV, produced in a single region of the jet. Considering the inverse Compton scattering on external photons and relativistic electrons in the jet as the emission process, as it is usually assumed, we have two possible scenarios. The emitting jet region could be inside of the Broad Line Region (BLR), where the external photons field would be the UV photons from the BLR or we can assume this emitting region to be outside of the BLR where the photon field would be composed of the IR photons coming from the torus. There are two important effects that need to be taken into account: the decreased efficiency of the IC scattering occuring in the Klein-Nishina (KN) regime and the absorption of γ-rays through pair production.

The energy above which the KN effects and γ-ray absorption become important in the case of UV external photons from the BLR is $\sim$ tens of GeV, and thus we would expect a cut-off at this energies if the emitting jet region is inside the BLR. But if we consider as target photons the ones coming from the IR torus this effect would start to be appreciated only at much higher energies above ≈ 1 TeV, because this effect depends on the frequency of the external target photons. Since there is no evidences of a cut-off at low energies we can conclude that the emission should come from outside of the BLR, as has been proposed by the “far dissipation" scenarios [e.g. [20]].

Besides, the other important result of the MAGIC observation is the fast variability, $t_{\rm var} \sim$ 10 minutes which indicates an extremely compact emission region. This is difficult to reconcile with the

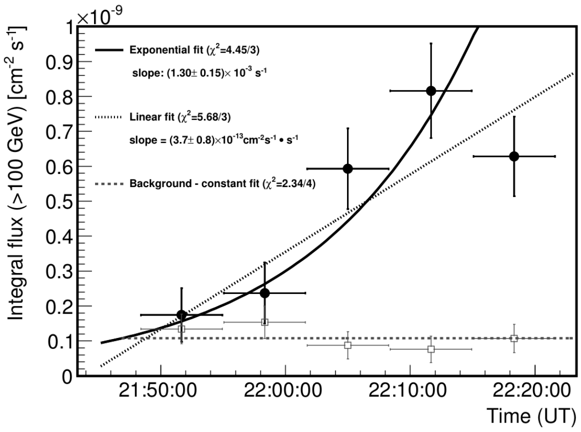

Figure 4: 4C +21.35 light curve above 100 GeV, in 6 minutes bins (black filled circles). The observation was carried out on MJD 55364. The black solid line is a fit with an exponential function and the black dotted line a fit with a linear function. The grey open squares denote the fluxes from the background events and the grey dashed line is a fit with a constant function to these points.

"far dissipation" scenarios if the emission takes place in the entire cross section of the jet since in this case the emitting region should be close to the central black hole and thus inside of the BLR.

Some explanations have been already proposed in order to solve this kind of incongruities, invoking the presence of very compact emission regions embedded within the large scale jet [21] or the possibility of a very strong jet recollimation [e.g. [22]].

In conclusion the MAGIC observations of VHE emission from the FSRQ 4C +21.35 set severe constraints on the emission models of blazar jets.

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